Evaluation of Brine Processing Technologies for Spacecraft Wastewater

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Brine drying systems may be used in spaceflight. There are several advantages to using brine processing technologies for long-duration human missions including a reduction in resupply requirements and achieving high water recovery ratios. The objective of this project was to evaluate four technologies for the drying of spacecraft water recycling system brine byproducts. The technologies tested were NASA's Forward Osmosis Brine Drying (FOBD), Paragon's Ionomer Water Processor (IWP), NASA's Brine Evaporation Bag (BEB) System, and UMPQUA's Ultrasonic Brine Dewatering System (UBDS). The purpose of this work was to evaluate the hardware using feed streams composed of brines similar to those generated on board the International Space Station (ISS) and future exploration missions. The brine formulations used for testing were the ISS Alternate Pretreatment and Solution 2 (Alt Pretreat). The brines were generated using the Wiped-film Rotating-disk (WFRD) evaporator, which is a vapor compression distillation system that is used to simulate the function of the ISS Urine Processor Assembly (UPA). Each system was evaluated based on the results from testing and Equivalent System Mass (ESM) calculations. A Quality Function Deployment (QFD) matrix was also developed as a method to compare the different technologies based on customer and engineering requirements.

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Nomenclature

BEB	=	Brine Evaporation Bag
FOBD	=	Forward Osmosis Brine Drying
UBDS	=	Ultrasonic Brine Dewatering System
IWP	=	Ionomer Water Processor
NSD	=	Nanomaterials Spray Dryer
OA	=	Osmotic Agent
DCMD	=	Direct Contact Membrane Distillation
EDU	=	Engineering Development Unit
ESP	=	Electrostatic Precipitator
WFRD	=	Wiped-film Rotating-disk
ESM	=	Equivalent System Mass
TS	=	Total Solids
TOC	=	Total Organic Carbon
EC	=	Electrical Conductivity
CM	=	Crew Member
QFD	=	Quality Function Deployment
ISS	=	International Space Station
WRR	=	Water Recovery Ratio

Solution 2 (Alt Pretreat) = ISS Augmented Urine, Pretreatment Chemicals, Hygiene Water, and Humidity Condensate
ISS Alternate Pretreatment = ISS Augmented Urine and Pretreatment Chemicals

I. Introduction

The objective of this study was to evaluate the NASA's Forward Osmosis Brine Drying (FOBD) system, Paragon's Ionomer Water Processor (IWP), NASA's Brine Evaporation Bag (BEB) system, and UMPQUA's Ultrasonic Brine Dewatering System (UBDS) for the drying of spacecraft water recycling system brine byproducts. The hardware was evaluated using feed streams composed of brines similar to those generated on board the International Space Station (ISS) and future exploration missions. This evaluation included both analysis and experimental testing. The testing element included operation of the technology with two brine formulations: ISS Alternate Pretreatment and Solution 2 (Alt Pretreat). The purpose of this testing was to down-select one technology, or to determine which technology would be best for treating spacecraft brine. A Quality Function Deployment (QFD) matrix was developed as a method to down-select a technology. This relationship matrix will be used to determine how well a technology's technical performance satisfies the customer's requirements.

II. Equipment Description

The FOBD, IWP, and BEB are membrane-based technologies, and the UBDS is a spray dryer that uses a nebulizer. A second spray dryer called the Nanomaterial Spray Dryer (NSD) was eliminated from the brine-testing program. The NSD was delivered to NASA by Nanomaterials Inc. through a SBIR Phase II contract. The NSD was based on an ultrasonic spray nozzle; however, the system was missing several components that were necessary for the system to operate including the ultrasonic sprayer and the condenser.

Each technology that was tested required a different initial volume of feed/brine: 375 mL for the FOBD, 400 mL for the BEB, approximately 14.0 L for the IWP, and 950 mL for the UBDS. During testing, liquid and gas samples were collected throughout each run; the FOBD did not require gas samples due to the lack of air flow. The mass reduction or volume reduction of the brine was recorded over time for all tests. The power consumption was recorded for the BEB and IWP. For the FOBD system, only the forward osmosis (FO) bag or membrane was tested and not the full system; therefore, no power was required. A brief description of each technology is provided below.

A. Forward Osmosis Brine Drying (FOBD)

The FOBD system is a technology being developed at NASA.[1] The system uses the Hydration Technologies XPack™, which is a forward osmosis (FO) bag. The bag consists of two compartments that are separated by an inner membrane, each with an inlet (feed and osmotic agent), as shown in Figure 1. The brine (375 mL) was placed on the inside of the membrane bladder (green inlet) and a concentrated solution (1 L) called the osmotic agent (OA), is placed on the outside of the membrane bladder (red inlet). The OA is a highly concentrated solution that has a higher osmotic

potential than the brine waste being dewatered. The OA solution dewaters the brine using osmotic forces to transfer water between the two solutions. The OA will then be regenerated by using a Membrane Evaporation (ME) system such as the Direct Contact Membrane Distillation (DCMD) system; however, this component was considered outside of the scope of this experimental work.[3]

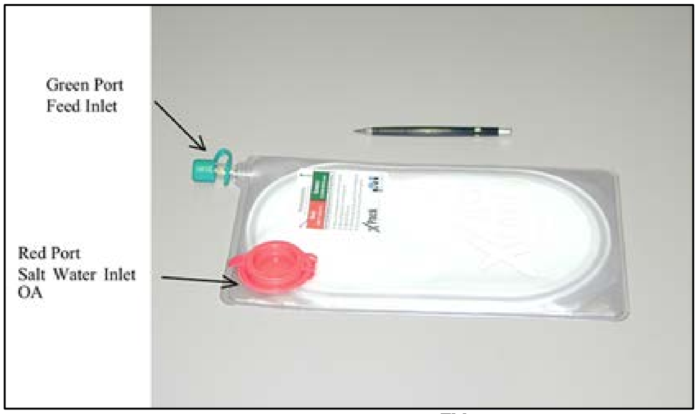

Figure 1. Hydration Technologies XPack^{TM}

B. Brine Evaporation Bag (BEB)

The Brine Evaporation Bag (BEB) is a technology being developed at NASA.[2] The BEB is a completely enclosed bag with a gas-permeable membrane (or membranes) installed within its sidewalls. The bag dewaters brine waste by removing volatiles and the liquid water as water vapor through the gas phase while keeping the liquid, solids, and other hazardous non-volatiles completely contained within the BEB.

The BEB Evaporator will provide the structural support for the BEB, the energy for the evaporation of the water from the brine within the BEB, and the vacuum to reduce the boiling point of the brine to make this a low temperature process. Proof-of-concept tests were conducted by placing a BEB within a vacuum oven to simulate the BEB Evaporator, as shown in Figure 2.

Figure 2. Breadboard BEB evaporator.

C. Ionomer Water Processor (IWP)

The Ionomer-membrane water processor (IWP) is a membrane-based technology being developed by Paragon Space Development.[8, 10] The system uses a large bag that contains a hydrophobic microporous membrane and a Nafion® membrane. Heated flowing air is introduced into the system, which causes the water in the bag to evaporate at the membrane outer surface. The hydrophobic ePTFE microporous membrane confines liquid water while allowing water vapor and other volatiles to pass through to the Nafion® membrane. The Nafion® membrane then further separates the water vapor from other unwanted constituents, primarily light hydrocarbons. A sweep gas carries away the water-saturated air. A polypropylene net encompasses the membrane pair for structural support.

Proof of concept has been demonstrated through a SBIR Phase I with Paragon. A Phase II SBIR under contract with Paragon to develop and build an Engineering Development Unit (EDU) was delivered in June 2014 to NASA

Ames Research Center. This Phase II system was used for the IWP testing conducted in this study, as shown in Figure 3.

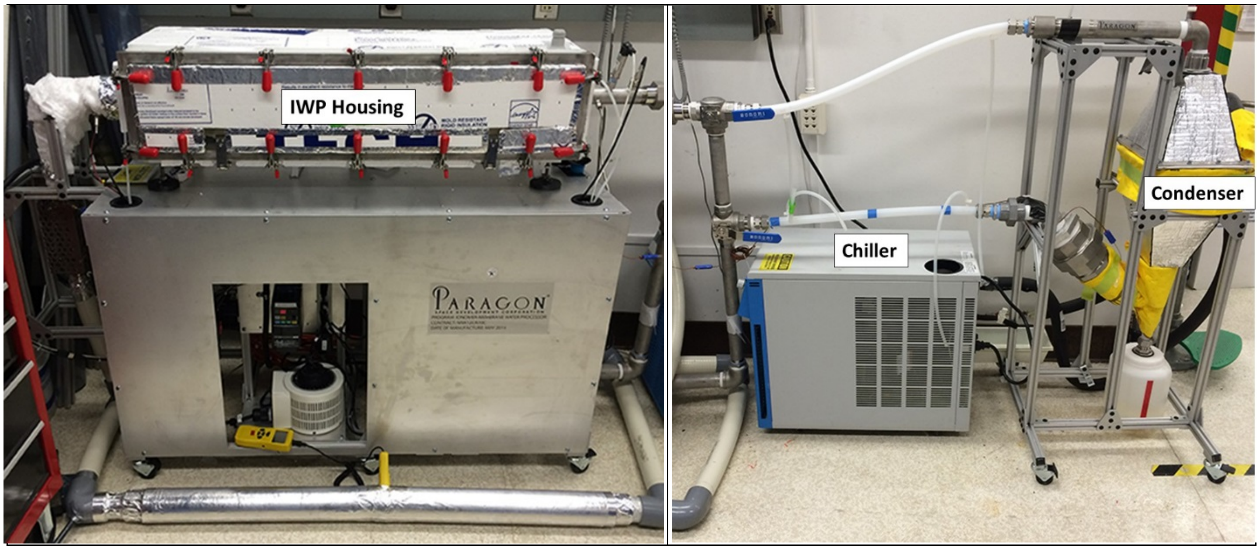

Figure 3. IWP system.

D. Ultrasonic Brine Dewatering System

The Ultrasonic Brine Dewatering System (UBDS) system was developed by the Umpqua Research Company to conduct nebulization-based droplet drying in suspension.[9] The system was constructed as part of a Phase II SBIR (NNX10CA21C), and was delivered to NASA Ames Research Center in 2012. The SBIR version of this system was intended to operate on planetary surfaces (e.g. Moon or Mars). The system design reflects these requirements and may not represent the future optimized system for microgravity space flight.

In UBDS, brine is nebulized into an air stream using focused ultrasonic waves at a water–air interface, forming a fine mist of brine droplets suspended in air. The mist then passes through a drying tube where it is heated to evaporate the water from the droplets, leaving behind fine dust particles composed of nearly water-free solids. The dust particle aerosol is removed from the water laden air stream using an electrostatic precipitator (ESP). The humid air that remains is cooled in a condenser to collect the water.

The mist is generated at the brine surface by focused sound waves in the ultrasonic range (greater than 20,000 Hertz). When a liquid is vibrated in a direction normal to its surface, capillary waves having a period that is double that of the initiating vibration are formed on its surface. This intense, standing-wave pattern ruptures forming micron-sized brine droplets (2-10 µm) at the gas-liquid interface. This mechanism results in a very fine spray without a nozzle. In addition to small droplet size, ultrasonic waves are very efficiently generated using a solid-state, piezoelectric transducer coupled to an AC electrical signal.

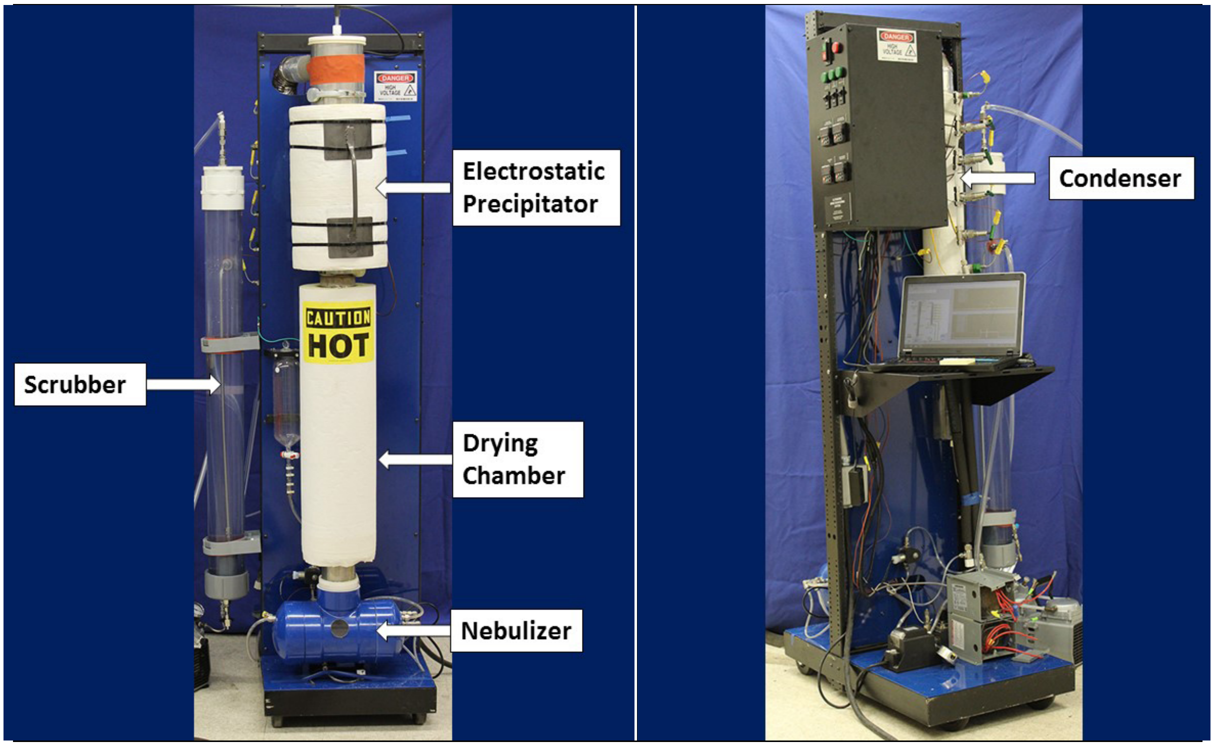

Figure 4. Ultrasonic Brine Dewatering System developed by UMPQUA.

III. Brine Generation

All tests were completed using the urine collected from male human donors. During the urine collection period, ice was used to keep the collection device and the urine cold. At the end of the workday, the urine was collected, supplemental pretreatment chemicals were added, and the urine was stored in the refrigerator. In addition, the urine was augmented to mimic on-orbit urine using a fixed augmentation procedure. The augmentation chemicals included supplemental organics and inorganics. The augmented urine was used to prepare two types of feed: the ISS Alternate Pretreatment[4] and the Solution 2 (Alt Pretreat)[5]. The difference between the two feeds was that Solution 2 (Alt Pretreat) contained hygiene water and simulated humidity condensate. For both feeds, the feed composition varied from batch to batch; this was due to the variation in the hygiene water and the urine, which were collected from human subjects. Once the feed was prepared, the feed was concentrated using a vapor compression distillation system.

A. ISS Alternate Pretreatment

The supplemental pretreatment chemicals that were added to the urine were based on the ISS Alternate Pretreatment formulation.[4] The ISS Alternate Pretreatment formulation consisted of the augmented urine, an acid, chromium trioxide, and deionized water. An acid was added to the oxidizer solution (chromium trioxide and deionized water), which was known as the Stabilizer solution (Table 1). The specific acid was selected to prevent calcium sulfate precipitation. The Stabilizer solution was added to the raw urine, and the urine was then stored in the refrigerator at 4 ± 2 °C until use.

In order to simulate on-orbit urine, augmentation chemicals (organics and inorganics) were added to the pretreated urine (raw urine and Stabilizer). Fixed amounts of these augmentation chemicals were added to the urine for all testing; these chemicals were not quantified in the urine prior to being added. The concentrations of the augmentation chemicals were based on historical data that defined the average concentration of the constituents of human urine.

To prepare the augmented urine, the pretreated urine (raw urine plus stabilizer) was mixed with the flush water (deionized water), organics (Erzatz Urine Organic Concentrate, Verostko 2010[4]), and inorganics ($CaCl_2 \cdot H_2O$, KH_2PO_4, and Na_2SO_4). The concentrations of the augmentation chemicals for the inorganics and organics are provided in Table 1 and Table 2 respectively. The total organic carbon (TOC) concentration of the pretreated urine was increased by adding the Ersatz Organic Concentrate (Verostko 2010)[4]. The organic components shown in Table 2 were added to deionized water resulting in a 1 L solution of the Ersatz Urine Organic Concentrate. For the ISS

Alternate Pretreatment feed, the feed mixture consisted of the Stabilizer solution, raw urine, augmentation chemicals, and flush water, as shown in Table 1.

Table 1. Concentrations for ground collected urine to on-orbit levels including pretreatment.

	mL/L of Urine	g/L of Urine
Ersatz Urine Organic Concentrate	76	
$CaCl_2 \cdot 2H_2O$		0.66
KH_2PO_4		3.10
Na_2SO_4		3.06
Flush Water *	113	
Stabilizer	19.5	

*Volume of Flush Water = 189 mL -Volume of Organic Concentrate
**Stabilizer is 17.5 mL/L of augmented urine

Table 2. Ersatz Urine Organic Concentrate.

Compound	Concentration mg/L
Urea	225.00
Taurine	16.14
Creatinine	13.33
Histidine	23.27
Glycine	18.02
Glutamine	15.20
Citric Acid	6.79
Glucuronic Acid	1.25
Serine	7.30
Alanine	6.15

B. Solution 2 (Alt Pretreat) Brine

The Solution 2 (Alt Pretreat) brine was used for testing to determine whether a technology could process brine derived from a waste stream containing surfactants. This feed solution contained augmented urine with the ISS Alternate Pretreatment (Table 1 and Table 2), humidity condensate[4], and hygiene water[5]. Table 3 shows the wastewater components and their concentrations. Hygiene water was generated from human subject shower water, hand wash, oral, and shaving water. Humidity condensate water was generated from a synthetic formula, which is shown in Table 5.

Table 3. Pretreated Urine, Humidity Condensate, and Hygiene wastewater (Solution 2) Composition.

Waste Stream			**Load**		
Component	(kg/event)	(events/CM-d)	(kg/CM-d)	(kg/crew-d)	(% by vol)
Augmented Urine	N/A	N/A	1.5	6	14.0%
Humidity Condensate	N/A	N/A	1.95	7.8	18.2%
Hygiene	N/A	N/A	7.24	28.95	67.8%
Oral	0.1	2	0.2	0.8	1.9%
Hand Wash	0.125	8	1	4	9.4%
Shower	6	1	6	24	56.1%
Shave	0.15	1/4*	0.038	0.15	0.4%
Total	--	--	10.69	42.75	100%

I. Personal Hygiene Products

The hygiene components included toothpaste, shaving cream, and body wash/shampoo. Arm & Hammer® toothpaste was used for the oral hygiene component, Neutrogena® Shave Cream was used as the shaving hygiene product, and the NASA formulation of No-Rinse® Shampoo was used for shower and hand wash activities.[5] The hand wash rinse quantity was based on informal human testing at Johnson Space Center (JSC). The shower water quantity was based on historic numbers from studies and testing at Marshall Space Flight Center (MSFC). Table 4 shows the quantity of product that was used for each hygiene activity.

Shower water was generated by collecting the wastewater that resulted after human subjects showered. A shower was limited to approximately 6 L of water and 25 g of No-Rinse® Shampoo. Shower water was generated by allowing the subject to shower for a defined time with a calibrated shower nozzle. Water was collected by blocking the shower drain and then pumping out the water from the shower pan and into a storage tank. Shower water was either used directly or refrigerated until use. Oral, hand wash, and shave water were also collected from human subjects. Human subjects performed these hygiene functions with the specified amount of water, toothpaste, and soap, and the resulting wastewater was collected.

Table 4. Personal hygiene product quantities per hygiene activity.

Hygiene Water		g/event	mL of water/event	Total mL/event
Oral	Arm & Hammer Toothpaste	1	100	101
Hand Wash	NoRinse Body Wash	1.5	125	126.5
Shower	NoRinse Body Wash	25	6000	6025
Shave	Neutrogena Men Shave Cream	0.8	150	150.8

II. Humidity Condensate

Table 5 shows the concentrations and components used to prepare the simulated humidity condensate. The simulated humidity condensate concentrate was prepared based on the transit mission wastewater ersatz formulation and preparation procedure determined by Verostko *et al.*, 2004.[11] The concentration of the humidity condensate concentrate was 50 mL per liter of wastewater.

Table 5. Composition of humidity condensate concentrate (50 mL /L of solution).

Name	Formula	MW	Concentrate (g)	Concentrate (mL)
Acetic acid	CH_3CO_2H	60.05	-	0.441
Benzoic acid	$C_6H_5CO_2H$	122.2	0.046	-
Benzyl alcohol	$C_6H_5CH_2OH$	108.14	-	0.259
Ethanol	C_2H_6O	46.07	-	1.506
Acetone	CH_3COCH_3	58.08	-	0.030
Caprolactam	$C_6H_{11}NO$	113.16	0.191	-
Phenol	C_6H_5OH	94.11	0.027	-
N,N-Dimethylformamide	$HCON(CH_3)_2$	73.1	-	0.035
Ethylene glycol	$HOCH_2CH_2OH$	62.07	-	0.157
4-ethyl morpholine	$C_6H_{13}NO$	115.18	-	0.072
Formaldehyde (37%)	HCHO	30.03	-	0.461
Formic acid (96%)	HCO_2H	46.03	-	0.208
Lactic acid	$CH_3CH(OH)CO_2H$	90.08	-	0.187
Methanol	CH_3OH	32.04	-	0.218
1,2-Propanediol	$C_3H_8O_2$	76.09	-	0.013
2-Propanol	$(CH_3)_2CHOH$	60.1	-	0.042
Propionic acid	$CH_3CH_2CO_2H$	74.08	-	0.042
Urea	NH_2CONH_2	60.06	0.101	-

C. Brine Production

Brine was produced from both types of feed: ISS Alternate Pretreatment and Solution 2 (Alt Pretreat). The feed was concentrated using the Wiped-film Rotating-disk (WFRD) evaporator.[6-7] The WFRD is a vapor compression distillation system that was used to simulate the function of the ISS Urine Processor Assembly (UPA). The WFRD was operated in a continuous mode where the flowrates of the feed, brine, and product were adjusted to values required for achieving the specified water recovery ratio (WRR). For the ISS Alternate Pretreatment, the WFRD was operated at 85% WRR (v/v). For the Solution 2 (Alt Pretreat), the WFRD was operated at a 95% WRR (v/v). The brine used for testing was the concentrated feed produced from the WFRD.

D. Analytical Test Plan

The brine and distillate samples were analyzed at NASA Ames laboratory for ionic composition (using ion liquid chromatography), pH, electrical conductivity (EC), TOC, density, and total solids (TS). The brine samples were sent to outside laboratories to test for levels of Cr(VI) and Cr(III). Table 6 provides a list of the measured parameters for the initial brine, distillate, and processed brine. Table 7 includes a list of analytical instruments used, and Table 8 shows a list of specifications for the ion chromatograph.

Table 6. Measured parameters for the initial brine, distillate, and processed brine (x = measured).

	Units	Brine	Product	Processed Brine
Na	ppm	x	x	-
NH_4	ppm	x	x	-
K	ppm	x	x	-
Mg	ppm	x	x	-
Ca	ppm	x	x	-
Cl	ppm	x	x	-
NO_2	ppm	x	x	-
Br	ppm	x	x	-
NO_3	ppm	x	x	-
PO_4	ppm	x	x	-
SO_4	ppm	x	x	-
pH	pH	x	x	x
TDS	%	x	x	x
TOC	ppm	x	x	x
Density	g/L	x	x	x
Cr(VI)	ppm	x	x	x
Cr(III)	ppm	x	x	x

Table 7. Analytical instruments.

Instrument / Hardware	Manufacturer	Model
pH Detector		
pH Meter	Thermo Scientific	Orion 3-Star
pH Probe	Thermo Scientific	9157BN
TOC analyzer	Shimadzu	TOC-VWS/P
TOC analyzer	Shimadzu	TOC-V CSH
Ion Chromatograph for Cations	Dionex	ICS-1500
Ion Chromatograph for Anions	Dionex	DX-500
Conductivity Meter		
Meter	YSI	3200
Probe	YSI	3252

Table 8. Ion chromatograph specifications.

Component	Anion Analysis	Cation Analysis
Model	ThermoScientific Ion Chromatograph, ICS-1600	Dionex Ion Chromatograph ICS-1500
Column	Ionpac AS4A w/AG4A Guard column	Ionpac CS12 w/CG12 Guard column
Suppressor	ASRS 300	CSRS 300
Detection	Conductivity	Conductivity
Eluent	1.8mM Na2CO3/1.7mM NaHCO3	20mM MSA
Flow Rate	2.0 ml/min	1.0 ml/min

IV. Summary of Experimental Results

The objective of the brine processor testing was to evaluate the FOBD, BEB, IWP, and UBDS using two different brines, which included the ISS Alternate Pretreatment and the Solution 2 (Alt Pretreat). This evaluation was partially based on the percent water recovery ratio (WRR) that each technology achieved as well as the gas and liquid sample analysis. The water recovery ratio was based on the ratio of the water produced divided by the initial volume of the water in the brine. In order to determine how much water was in the brine, TS analysis was conducted. The drying protocol for the FOBD and IWP samples followed Standard Method 2540 B (Total Solids Dried at 103–105°C); BEB samples followed a modified protocol. Both drying techniques required a lower temperature to prevent the decomposition of components due to heat. The target water recovery ratio for each technology was 86.7% for the ISS Alternate Pretreatment, and 84.4% for Solution 2 (Alt Pretreat). The results from testing are shown in Table 9, Table 10, and Table 11 for the FOBD, BEB, and IWP respectively. Each system was required to complete each test in triplicate although only the FOBD completed triplicates of all tests. The UBDS completed one run due to plugging of the system. The IWP was only able to complete one run that reached the maximum water recovery ratio although other shorter runs were competed[10]. The BEB completed triplicate runs for the ISS Alternate Pretreatment, although the final sample from Run 1 was lost and could not be analyzed for the WRR.

A. FOBD

Table 9 shows the results from all FOBD system tests. Three different osmotic agents were tested: sodium chloride (NaCl) solution (350 g/L in deionized water), NaCl solid salt, and lithium chloride (LiCl) solution (700 g/L in deionized water). Three tests using three different bags were conducted for each type of osmotic agent/brine test in order to calculate the average values and errors. The FOBD met the target water recovery ratio for Solution 2 (Alt Pretreat) brine using a NaCl solution as the osmotic agent. The FOBD met the target water recovery ratio for the ISS Alternate Pretreat using a LiCl solution as the osmotic agent (OA); the NaCl solution did not meet the target WRR. The FOBD was not tested as a complete system and requires a method to reconstitute the OA such as Direct Contact Membrane Distillation (DCMD). DCMD has been extensively tested by NASA, and as a result, testing of the DCMD was considered outside of the scope of this experimental work.

Table 9. Results and analysis from FOBD testing.

		ISS Alternate Pretreat NaCl Solution	Solution 2: Alt Pretreat NaCl Solution	ISS Alternate Pretreat NaCl Solid Salt	ISS Alternate Pretreat LiCl Solution
Initial Brine Volume	mL	375	375	375	375
Density of Brine	g/mL	1.15	1.08	1.20	1.16
Volume Recovered	mL	268 ± 8	311 ± 9	NA	267 ± 9
Mass Recovered	g	NA	NA	199	NA
Volume Reduction	%	71	83	NA	71
Mass Water RR	%	79.7 ± 2.0	89.4 ± 0.3	76.8 ± 5.1	88.2 ± 6.7
Target Water RR	%	86.7	84.4	86.7	86.7

B. BEB

Table 10 shows the results for all BEB testing. The BEB met the target water recovery ratio for the ISS Alternate Pretreat; three runs were successfully completed. However, only samples from Run 2 and Run 3 were analyzed for TS, which was used to calculate the water recovery ratio. Additionally, based on experimental testing, the BEB failed the tests using the Solution 2 (Alt Pretreat), or brine that contained surfactants; this failure was due to leakage of the membrane.

Table 10. Results and analysis from BEB testing.

		ISS Alternative Pretreat			Solution 2: Alt Pretreat		
		Run 1	Run 2	Run 3	Run 1	Run 2	Run 3
Brine Residue	g	131.5	131.6	129.3	68.8	73.3	64.8
Initial Brine Mass	g	450.0	452.4	444.1	420.0	423.2	425.6
Mass Reduction	%	71.0	71.0	71.0	84.0	83.0	85.0
Water in Residue*	%		292.0	286.7	10.7	9.8	
Water RR	%		38.1	37.4	97.9	98.1	
Target Water RR	%	86.7	86.7	86.7	84.4	84.4	84.4

*Percent water in residue is an average that was based on drying two samples of the remaining brine for ISS Alternate Pretreat Run 2 and Run 3

C. IWP

Several tests were conducted to determine the optimum operating conditions for the IWP; some of these tests were completed prior to the delivery of the system at NASA at Paragon Space Development Corporation.[10] A test was conducted at NASA Ames Research Center to determine the maximum water recovery ratio for the ISS Alternate Pretreatment brine. This test showed that the maximum water recovery that can be achieved by the IWP was 87.2%, which is shown in Table 11. This water recovery ratio exceeded the target of 86.7%.

Based on experimental testing, the IWP failed the tests using the Solution 2 (Alt Pretreat) or the brine that contained surfactants. The brine seeped through the ePTFE membrane, but appeared to be retained by the Nafion® membrane. Although the hydrophobic membrane worked well for the ISS Alternate Pretreatment, a different membrane or bag design is required for the Solution 2 (Alt Pretreat) brine due to the surfactants. Additionally, an issue was discovered with the seams of the IWP bags; the seams leaked because Teflon® and Nafion® are difficult to seal.

Table 11. Results and analysis from IWP testing.

		ISS Alternate Pretreat NaCl Solution
Initial Brine Volume	kg	16.29
Initial Density of Brine	g/mL	1.16
Final Density of Brine	g/mL	1.42
Mass Recovered	kg	9.9
Mass Reduction	%	61.3
Mass Water RR	%	87.2
Target Water RR	%	86.7

D. UBDS

For the Ultrasonic Brine Dewatering System, 1 L of brine was processed in approximately 5.1 h at a water production rate of 141.2 mL/h; 720 mL of the condensate was collected. The system met the target for the ISS Alternate Pretreatment brine; however, only one run was completed due to a buildup of solids within the system. Based on visual inspection of the system, a solid material formed above the baffles, as shown in Figure 5. This material would be very difficult to remove as well as unsafe; therefore, the testing of the UBDS was discontinued.


Figure 5. Middle of UBDS system (above baffles).

E. Specific Power and Sample Analysis for FOBD, BEB, IWP, and UBDS

I. Specific Power

The specific energy was determined for each system, as shown in Table 12. The FOBD specific energy value came from prior DCMD testing.[1] The UBDS specific energy was determined using the values provided by UMPQUA.

Table 12. Specific energy values for FOBD, BEB, IWP, and UBDS.

System	Specific Energy (kWh/L)	
	ISS Alternate Pretreat	Solution 2 (Alt Pretreat)
FOBD	1.70*	
BEB	5.02	11.50
IWP	7.73	-
UBDS	3.47**	-

*FOBD value came from prior DCMD testing
**UBDS value was calculated using the energy consumption reported in the UBDS SBIR2 final report

II. Liquid Sample Analysis

Samples were analyzed for chromium by Accutest Laboratories (BEB, UBDS, and IWP) and Torrent Laboratories (FOBD). The Cr(VI) analysis for the BEB showed that the Cr(VI) concentration was less than their detection limit and had <0.35 ppm Cr(III). The FOBD system also demonstrated the ability to process the ISS Alternate Pretreat brine without leaking Cr(VI). The IWP and UBDS leaked less than 0.2 ppm Cr(VI); and for total chromium, the UBDS leaked 2.6 mg/L and the IWP leaked 0.22 mg/L. The FOBD leaked 3.6 ± 1.4 mg/L of trivalent chromium for the Solution 2 (Alt Pretreat) and 0.76 ± 0.26 mg/L for the ISS Alternate Pretreatment brine. However, all samples for each technology were not analyzed within 24 hours. For accurate chromium analysis, samples must be analyzed within 24 hours or the hexavalent chromium will break down into trivalent chromium over time.

In addition to chromium analysis, samples were collected of the condensate for all systems except for the FOBD. For the FOBD, samples were collected from the OA. Table 13 shows the initial and final TOC values for the FOBD and IWP; samples were only collected at the end of the run for the BEB and UBDS. Based on the analytical results, the total organic carbon (TOC) concentration for the FOBD was the highest. The IWP had the lowest initial TOC although the TOC increased throughout the duration of each test resulting in a final TOC value of approximately 500 ppm. The BEB had the lowest final TOC concentration of the condensate; however, the initial feed volume was much less compared to the IWP. The BEB only processed 400 mL compared to the IWP, which processed 14.0 L of brine. The results from the IWP indicate that TOC may also be a function of the operating temperature (air flow temperature) or water recovery ratio. More work needs to be conducted to determine this relationship. To compare the results from all systems, samples must be collected over time and a single sample from the final total product water must be collected as well.

Table 13. TOC values for FOBD, BEB, IWP, and UBDS.

System	ISS Alternate Pretreat Condensate TOC (ppm)		Solution 2 (Alt Pretreat) Condensate TOC (ppm)		Feed Volume (mL)
	Initial	Final	Initial	Final	Initial
FOBD	8049 ± 2208	2132 ± 256	6964 ± 441	468 ± 107	375
BEB	-	192 ± 12	-	274 ± 175	400
IWP	51.1	215	-	-	13999
UBDS	-	1698	-	-	950

III. Gas Sample Analysis

Delzeit *et al.*, 2015, discusses the details of the GCMS analysis for all testing of the BEB, UBDS, and IWP.[3] The composition of the organics observed from the IWP effluent gas consisted of aliphatic and aromatic hydrocarbons, which also contain oxygen and sulfur. The effluent gas of the UBDS also contained those species, but included nitrogenous compounds. Those nitrogenous compounds are believed to be formed from the high temperature reaction of the oxygenous species identified from the IWP reacting with ammonia. This reaction results in the nitrogen substitution of the oxygen.[3]

Figure 6 shows the GCMS analysis of the effluent gas samples, which indicates there are some significant differences in the concentration and composition between the IWP, UBDS, and BEB samples[3]. However, the BEB and UBDS samples were collected after the condenser and the IWP samples were collected before the condenser. Samples collected after the condenser are affected by the temperature of the condenser and solubility (Henry's Law); this may result in a lower concentration of contaminants. Additional testing must be conducted in order to directly compare the results from the IWP, BEB, and UBDS.

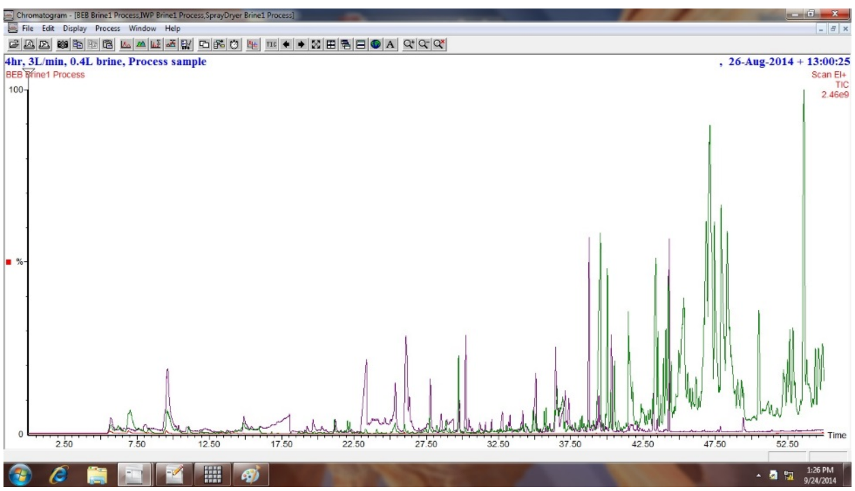

Figure 6. The chromatograms of the BEB (red), IWP (green), and SprayDryer (purple) are shown, all on the same scale. The chromatogram for the BEB (red), on this scale, is at the baseline.[3]

V. Equivalent System Mass

In addition to experimental testing and sample analysis, the Equivalent System Mass (ESM) was calculated for each technology and each pretreatment. The ESM is a single number that is calculated based on specific parameters or physical quantities that describe a system/subsystem including mass, power, and volume.[12] NASA uses ESM to represent the feasibility of a system for a specific mission; systems with a lower ESM have a greater chance of being launched into space than those with a higher ESM.

A. ESM Assumptions and Calculations

The ESM was calculated for a 360-day long Mars transit mission and a crew of four. Table 14 shows the daily water values used for each pretreatment as well as the water recovery ratios required. The overall RR is the recovery ratio for the overall water loop closure. The WFRD RR is the water recovery ratio required for the primary water

processor (WFRD), and the Brine RR is the water recovery ratio for the brine processor that is required to achieve the overall RR.

For daily water used, the hygiene water value came from the Alternate Water Processor (AWP) Integrated Test Wastewater Definition and Collection Document.[5] For the ISS Alternate Pretreatment, the Mars transit mission values were used from the 2008 Advanced Life Support Baseline Values and Assumptions Document (BVAD).[12] The make-up water (water from food) for the hygiene water was assumed the same as the ISS Alternate Pretreatment. If the percent brine water recovery ratio was below the target value, then the makeup water to reach the target was included in the ESM calculation.

The ESM values for each technology are shown in Table 15. This includes ESM values for the current system for the FOBD, BEB, and IWP. The mass, power, and volume values used to determine ESM are shown in Table 16. The crew time estimates were not included and depend on the flight system design. The ESM for the FOBD was calculated based on using a LiCl solution as the osmotic agent; a NaCl solution was used as the osmotic agent for the Solution 2 (Alt Pretreat) ESM.[1] The resupply for FOBD includes the membrane bags and salt; the resupply for BEB and IWP includes only the bags. The UBDS has no resupply or consumables.

Table 14. Values used for calculating ESM.

	Pretreatment	Daily Water Used	Overall RR	WFRD RR	Brine RR
		kg/CM-d	%	%	%
1	Solution 2: Alt Pretreat	10.69	99.2	95.0	84.4
2	ISS Alternate Pretreatment	4.163	98.0	85.0	86.7
	2a) Urine	1.886			
	2b) Humidity Condensate	2.227			

Table 15. ESM values for FOBD, BEB, IWP, and UBDS.

Technology	Current ESM	
	ISS Alternate Pretreat	Solution 2 (Alt Pretreat)
FOBD	95	86
BEB	77	
IWP	293	
UBDS	247	

Table 16. Current system mass, power, and volume values for FOBD, BEB, IWP, and UBDS.

System	Pretreatment	Mass (kg)	Power (kW)	Volume (m^3)
FOBD	ISS Alternate Pretreat	8.49	0.15	0.02
	Solution 2 (Alt Pretreat)	35.61	0.15	0.15
IWP	ISS Alternate Pretreat	133.40	0.37	0.69
BEB	ISS Alternate Pretreat	24.40	0.31	0.01
	Solution 2 (Alt Pretreat)	28.40	0.43	0.02
UBDS	ISS Alternate Pretreat	118.77	1.06	0.27

VI. Discussion

The results from this study indicate that the FOBD is the only system that met the target WRR for both the ISS Alternate Pretreat brine and the Solution 2 (Alt Pretreat) brine. However, only the FOBD bag was tested and not the complete system with an OA regeneration system; the BEB, IWP, and UBDS, were all tested as complete systems. The salt resupply or the amount of salt lost by the FOBD membrane must be also be determined for an accurate ESM value.

Additionally, the UBDS system plugged after the first run and testing was discontinued due to safety concerns. Despite this failure, other spray drying technologies designed specifically for dealing with viscous brines may be

successful at treating brines for space applications. The testing conducted by UMPQUA showed that the UBDS functioned; the testing at Ames showed that the system does not work specifically for the ISS Alternate Pretreatment brine.[13] There are two hypotheses that may explain why the system failed or why the solids formed: the first is the electrostatic precipitator and the second is IR heater.

The first hypothesis is that due to system design and the placement of the baffles, the solids were pushed to the walls that were adjacent to the electrostatic precipitator. These solids would then slide down until reaching the baffles. Over time, the solids would build up until the system was completely plugged, which prevented air from flowing within the system. This hypothesis was based on visual inspection of the system; the walls surrounding the electrostatic precipitator appeared to be clean indicating that the buildup might be due to the electrostatic precipitator.

The second hypothesis is that the IR heater is very hot and burns the organics prior to reaching the precipitator. Subsequently, a char is formed resulting in the plugging of the system. This appears to follow the results from the GCMS.[3] In order to determine which hypothesis is correct, Small Sample Brine Drying (SSBD) testing may be conducted. This testing would determine the consistency and morphology of the dried samples depending on the drying process conditions.

Testing also needs to be conducted to determine whether Nafion® may be used with surfactants. The BEB and IWP failed the testing using the Solution 2 (Alt Pretreat) brine, which contained surfactants. This failure was due to the membranes leaking. Testing of the IWP and literature has demonstrated that a PTFE ion-channel membrane such as Nafion® may not susceptible to surfactants and could work well for this application. The hydrophobic ePTFE membrane is susceptible to surfactant fouling. Nafion® membrane permeability rates are also affected by the ions of the solution it is in contact with.

In addition to membrane leakage when using surfactants, the IWP has the highest ESM. However, this system may be optimized by adding heaters to the bottom of the bag. Table 17 and 18 show the optimized values for the BEB and IWP. BEB may be optimized by replacing the Air Squared V16 scroll pump with the Air Squared V11 scroll pump, which is much lighter and uses less power, and by increasing the size of the membranes. Increasing the membrane size would reduce the number of bags or bag change outs that are required, and would slightly increase the mass.[2]

Table 17. ESM values for FOBD, BEB, IWP, and UBDS.

Technology	Current ESM		Optimized System ESM
	ISS Alternate Pretreat	Solution 2 (Alt Pretreat)	ISS Alt Pretreat
FOBD	95	86	
BEB	77		39
IWP	293		98
UBDS	247		

Table 18. Mass, power, and volume values for FOBD, BEB, IWP, and UBDS.

System	State	Pretreatment	Mass (kg)	Power (kW)	Volume (m^3)
FOBD	Current System	ISS Alternate Pretreat	8.49	0.15	0.02
	Current System	Solution 2 (Alt Pretreat)	35.61	0.15	0.15
IWP	Current System	ISS Alternate Pretreat	133.40	0.37	0.69
	Optimized	ISS Alternate Pretreat	70.40	0.15	0.09
BEB	Current System	ISS Alternate Pretreat	24.40	0.31	0.01
	Optimized	ISS Alternate Pretreat	20.20	0.13	0.01
UBDS	Current System	ISS Alternate Pretreat	118.77	1.06	0.27

Lastly, all systems, FOBD, IWP, BEB, and UBDS may be designed to be compatible in microgravity. The function of the FO bag has been verified in flight. This testing verified that the FO process works in microgravity and the bag can be filled and product can be removed from it. It also showed contaminate rejection is unchanged compared to on the ground, but there is a reduction in flux across the membrane in microgravity. This was a qualitative test and more

flight-testing needs to be done to quantify this reduction and develop mitigation approaches.[1] Furthermore, development testing must be conducted for the BEB and IWP to determine an appropriate design.

VII. Quality Function Deployment

Based on the results from the FOBD, IWP, BEB, and UBDS testing, there is no technology that appears to be the best choice for brine processing. Additionally, down-selecting a technology can be very complex; several factors must be taken into consideration including the requirements for a specific mission. As a result, to simply this task, the four technologies may be compared using a Quality Function Deployment (QFD) matrix.

QFD is used to trace functional requirements back to the customer and the user requirements.[8] A relationship matrix was used to determine how well a technology's technical performance satisfies the customer's requirements. Customer requirements are rated in importance by the customer, and the relationship matrix is weighted on how strong a particular functional requirement has an effect on a customer requirement. QFD has been employed by companies worldwide for new products, six-sigma process improvement, and ISO 9000 quality management. QFD has been proposed as a method to assist in the technology selection process.

Figure 7 displays the QFD matrix. Rows 1-13 identify customer and user requirements and columns 1-16 capture functional requirements (above the blue matrix) and target criteria (below the blue matrix). The relationship matrix itself (blue cells) captures the relationship strength between customer requirements and functional requirements. Customer requirements' rated importance is shown in the green column.

In this study, the purpose of the QFD chart was to determine what requirements are most important to the customer as well as to make the engineers aware of these requirements during development. In general, the QFD chart will be used to assist in the down-select of a brine processing technology. The customer requirement importance was rated by the NASA Advanced Exploration Systems (AES) Life Support Systems (LSS) project management. The NASA Ames team completed the strength relationship matrix as well as the weighting relationship between the customer and functional requirements, as shown in Figure 7.

Relationships	
Strong	●
Moderate	○
Weak	▽

Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
	Valuation Metrics			Technical										Operations	
Direction of improvement towards target metric	◇	▼	▼	◇	◇	▲	◇		◇	▼	▼	◇	◇	▼	▼
Relative Weight	8%	6%	5%	12%	6%	6%	6%	4%	1%	5%	5%	1%	8%	8%	12%
Technical Importance Rating	317	259	219	470	247	238	261	182	35.6	206	206	34	326	332	488
Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9	9	9	9
Functional Requirements (Hows)	TRL	ISS Consumables	ISS Experiment Equipment Mass	Adherence to WRS requirements	Adherence to cabin air quality requirements	Amount water recovered from brine	Containment and Storage	Management of Brine	Scalability	ISS Power and cooling limits	ISS Volume limits	ISS Noise/Vibration	Micro-g operation	ISS Crew Operation time	Reliability and Maintainability

	Row #	Relative Weight	Customer Importance (1-9)	Maximum Relationship	Customer (AES, Mission Mgrs, Astronauts, etc.) Requirements (Whats; Wants)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Performance	1	11%	9	9	Easy/Safe handling of brine & residual & solids	▽	▽	▽	▽			●	●		▽	▽		●	○	○
	2	6%	4.5	3	Handles a variety of brine															○
	3	9%	7	9	High water recovery ratio	○	●	●	●		●	▽			○	○				▽
	4	9%	7	9	Mission Cost (ESM, etc.)	▽	●	●	▽	▽	●	○			●	●		▽	●	○
	5	2%	1.5	9	Flight Experiment Cost	○	○	●		○				●	●	●		●	●	○
-ilities	6	6%	5	9	Reliability and confidence in the system	●	○	▽	●		●	▽		○				●	●	●
	7	4%	3	9	Acceptable human factors	○	▽			●		▽	○				●	▽	●	●
	8	9%	7.5	9	Low maintenance	▽	▽	▽	○	▽		▽	▽						○	●
	9	9%	7.5	9	Simple operation	▽	○	▽	○	●		▽	○					▽	○	○
Integ	10	8%	6.5	9	Integrates with planned flight systems	●	○	▽	●	●	○				●	●		○	○	▽
Safet	11	11%	8.5	9	Safety	●			●	○		●	○					●	○	●
Cost	12	10%	8	9	Quality of recovered water	▽			●									▽		●
		100%	80																	
					Target criteria based on Functional Requirements	TRL ≥ 4	<0.3 kg/mo	< 30kg	Satisfies WRS requirements	Satisfies SMAC	≥86.7% for alt pretreat	Completely contained	Minimal handling and transfer between	Tested at > 70% full scale	<100W avg; <400W peak	<0.2 m^3 (mid-deck locker)		<1 micro-g	crew time < 0.5 hr/week	MTBF > 2 yrs

Customer Competitive Assesment	FO	IWP	BEB	UBDS
Weight Chart	###	###	###	###
Relative Weight	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Technical Importance Rating	0	0	0	0
	0	0	0	0

Technical Competitive Assesment					
FO	0	0			
IWP	0		0		
BEB	0			0	
UBDS	0				0

Figure 7. QFD chart for evaluating the FOBD, BEB, IWP, and UBDS.

VIII. Conclusions

All systems were able to reach the target water recovery ratio for the ISS Alternate Pretreatment brine. However, the UBDS and IWP only completed one run, and the BEB and FOBD completed triplicate runs. The IWP successfully treated the ISS Alternate Pretreatment brine although there was an issue with the seams leaking on the IWP bag. The BEB and IWP membranes leaked when using the Solution 2 (Alt Pretreat) brine. The FOBD system was able to treat both the Solution 2 (Alt Pretreat) brine and the ISS Alternate Pretreat brine using a NaCl solution and LiCl solution as the osmotic agents respectively.

The BEB had the lowest ESM of the three systems tested for the ISS Alternate Pretreatment brine. All membrane-based systems (IWP, FOBD, and BEB) require consumables and resupply. The FOBD, IWP, and BEB require

replacement bags, and the FOBD requires additional salt for the osmotic agent. The amount of resupply for each system has not been experimentally determined; some bags may be reused.

The BEB and FOBD System demonstrated the ability to process ISS Alternate Pretreat brine without leaking Cr(VI). However, samples must be analyzed within 24 hours for accurate hexavalent chromium values. IWP and UBDS leaked less than 0.2 ppm Cr(VI); for total chromium, the UBDS leaked 2.6 mg/L and the IWP leaked 0.22 mg/L. The FOBD leaked 3.6 ± 1.4 mg/L for the Solution 2 (Alt Pretreat) and 0.76 ± 0.26 mg/L for the ISS Alternate Pretreatment; these samples only contained trivalent chromium.

The UBDS was unable to complete all tests and subsequently failed. The first test was able to reach completion; however, during the second test a pump failure occurred. After visual inspection of the system, it was determined that a solid material located above the baffles caused the system to plug after processing 1 L of brine.

IX. Future Work

Based on the results from testing all technologies, further work is needed in order to down-select a technology. Specific tasks for each system will be completed in the next fiscal year. All future testing will be conducted using only the ISS Alternate Pretreatment brine. The QFD chart will also be completed to assist in determining which technology should be selected.

Future work for the FOBD system includes modifying the XPack™ bag to resolve dead space limitations, evaluating the use of Alternate OA solutes, determining membrane life, constructing a prototype OA regeneration system, and constructing a continuous flow FO contractor that will be integrated with the DCMD. For the BEB system, future tasks include developing a continuous-flow system, determining brine drying characteristics, scaling up the BEB evaporator, investigating Nafion® membranes, and investigating system performance based upon vacuum and pump characteristics. The IWP tasks include developing more reliable seams for membrane bags (Phase III SBIR to Paragon Inc.), determining number of uses per bag, and determining the effect of direct contact heating. Lastly, the spray dryer tasks include completing drop formation drying laboratory testing. The objective for the laboratory testing is to distinguish whether the residual dry solids were due to pyrolization of the brine in the UMPQUA spray dryer, or if they were an inherent characteristic of spray dryers in general. This will help to determine the feasibility of spray dryers for space flight missions.

Appendix

A. IWP ESM

ESM for the ISS Alternate Pretreatment is 293 kg. Resupply of membrane bags for a 360-day, 4-crew mission is 18 bags at 0.3 kg/bag.

ESM computations for the two cases:

1. Case 1 IWP as tested ESM is 297kg
2. Case 2 Optimized IWP with embedded heaters in bag and insulated EDU housing ESM is 98kg

Assumptions:

The latent heat of water is 2260 J/g
Density of water is 1g/ml
Reference mission – mission to Mars, one year transit, crew of four
Process 28 liters of brine over 21 days for one year
Number of bags = 365/21 = 17.4 = 18 bags
As tested volume total volume: 50” x 42” x 20” = 42,000 cu in = 0.688m^3 (includes EDU housing, blower and heater and instruments)
As tested EDU housing volume: 43” x 15” x 10” = 6450 cu in = 0.106m^3
As tested blower volume: 14” x 14” x 14” = 2744 cu in = 0.045m^3
As tested instruments: 8” x 8” x 8” = 512 cu in = 0.0084m^3
k_p=13.7 ml/hr*C*m^2

ESM Calculations:

Case 1.

a. The amount of recoverable water in 28 liters of brine at 86.7% recoverable water is 24.28 liters.. To recover this amount of water over 21 days requires a water production rate of 1.156 liters/day or 48.2 ml/hr.
b. 48.2 ml/hr water recovery rate corresponds to a minimum ideal power requirement of 48.2*2260/3600=30.2W
c. At an efficiency ratio of 0.27 (as determined from the data of BT2 and BT3) this corresponds to a required heater + instrument power of 30.2/.27=112.0 W for both heater and instruments/controller.
d. Add blower power of 220W
e. Total power as tested = 332W
f. As tested membrane bag surface area is 794 sq in = 5123 cm^2
g. Volume of 18 bags at 1 cm thickness = 18 x 0.512 m^2 x .01 m = 0.005 m^3
h. Volume as tested 0.688m^3. Note, the system as tested is inefficiently packaged.
i. Cooling required to condense 48.2 ml/hr is 30.2W.

Case 2: ESM power using a more efficient embedded heater system with good insulation to achieve a maximum water recovery ratio of 86.7%

j. Amount of available water for recovery is 24.28 liters. To recover this amount of water over 21 days requires a water production rate of 1.156 liters/day or 48.2 ml/hr.
k. 48.2 ml/hr water recovery rate corresponds to a minimum ideal power requirement of 48.2*2260/3600=30.2W
l. At an efficiency ratio of 0.8 for an imbedded bag heater, well insulated system operating at mild heater and temperature conditions (high heater specific energy), this corresponds to a required heater + instrument power of 30.2W/0.8 = 37.75W for both heater and instrument.
m. Add an efficient blower of 116W (Paragon ref: ISS CDRA blower)
n. Total power for highly efficient system = 153.75 W.
o. The required surface area for $\square_p$=70C and k=13.7 ml/hr*C*m^2 and a permeation of 48.2ml/hr is 0.35m^2 = 542.5 in^2. This is 68% of as tested bag area.
p. Initial mass. Take Paragon value of = 13 kg
q. Volume of 18 bags = 0.005 m^3
r. Volume of EDU for 28 liter (0.028m^3) bag fill plus electronics. Take Paragon value of 0.08 m^3

Cooling required to condense 48.2 ml/hr is 30.2W

B. UBDS ESM

ESM for the ISS Alternate Pretreatment is 297 kg. The weight of the UBDS delivered to Ames, not including the chiller, was approximately 106.9 kg. However, according to UMPQUA the actual components are about half of that weight; the other half is due to the frame. Therefore, assuming the component weight is correct; an extra 10 kg was added for an optimal frame. Table 1 shows a list of components and their respective weights, which was provided by UMPQUA. The chiller values were based on the actual chiller provided by UMPQUA; however, a flight rated system would weigh much less. The power number was also provided by UMPQUA; this number was not determined from testing since testing was incomplete due to failures.

Table 1. UBDS components and weight.

Component	Mass (kg)
Ultrasonic Nebulizer	1.115
Nebulization Chamber	4.9
Drying Tube	5.384
Mounts	1.814
Silica Wool Insulation	0.5
Drying Tube Outer Insulation	1
ESP+ Heat Tape + Insulation	3.175
ESP Chamber and Electrodes	1.188
Clamps for Mounting ESP	0.245
Ducting from ESP to Condenser	1.361
Condenser	3.552
Condenser Insulation	0.25
Valves	1.188
Tubing + Fittings	0.454
Mass Flow Controller	2.404
Solenoid Valves	0.8
Brine Reservoir	0.35
Condensate Container	0.17
Computer/DAQ/Thermocouple Reader	2.722
Computer Power Supply	0.227
24 VAC Power Supply	5.216
24 VDC Power Supply	0.454
Temperature Controllers g	0.707
SSR Power Controllers	0.9
Spellman HV Power Supply	0.204
DIN Rails	0.439
Relay	0.2
Switches + Lights	0.227
Wire + DIN Blocks	0.907
Total =	42.05

Acknowledgments

Special thank you to everyone that donated urine at NASA Ames Research Center to make completing this testing possible.

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